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喇曼放大器噪声对性能的影响

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摘要: 对拉曼放大器(RA)的放大自发辐射(ASE)噪声、等效自发辐射因子、等效噪声系数以及 RA 中的 ASE 噪声、瑞利噪声、光纤长度和开关增益分别对光接收机信噪比的影响进行了理论分析, 并对双重瑞利背向散射噪声进行了理论计算和相关数值仿真。计算与仿真结果表明: 在同一信号输入条件下, RA 相对掺铒光纤放大器(EDFA)能提高光接收机的信噪比; RA 的等效自发辐射因子 <1 且其随开关增益的增加而减小, 因而优于 EDFA; RA 的瑞利噪声可以忽略的条件为 RA 的增益 <15 dB; 文中还得到对优化设计 RA 具有重要参考价值的一些其它结论。

关键词: 拉曼放大器(RA); 放大自发辐射(ASE)噪声; 瑞利噪声; 双重瑞利背向散射; 信噪比

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Impact of noises in Raman amplifier on its performance

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Abstract: The Amplified Spontaneous Emission (ASE) noise, equivalent spontaneous emission factor and equivalent noise factor for the Raman Amplifier (RA) as well as the respective impacts of the ASE noise, Rayleigh noise, optical fiber length and the switching gain in the RA on the Signal Noise Ratio (SNR) of optical receivers are theoretically analyzed, and then the Double Rayleigh Backscattering (DRB) noise are also theoretically analyzed and calculated. Furthermore, the numerically related simulations are also implemented. The calculation and simulation results show that, compared with the Erbium-Doped Fiber Amplifier (EDFA), the RA can improve the SNR of optical receivers under the condition of the same input signal; the equivalent spontaneous emission factor is less than 1 and decreases with the increase of the switching gain, so this characteristics of the RA are superior to that of the EDFA. Moreover, when the gain of the RA is less than 15 dB the Rayleigh noise of the RA can be ignored. Also, some other significant conclusions to play the important roles in guiding the optimal design of the RA are obtained.

Key words: Raman Amplifier (RA); Amplified Spontaneous Emission (ASE) noise; Rayleigh noise; double Rayleigh backscattering (DRB); Signal Noise Ratio (SNR)

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1 Introduction

Raman amplifiers (RA) have advantages such as higher gains, wider bandwidths, smaller Noise Factors (NF) and better temperature stability and can implement the amplification for the optical signals at any waveband. Therefore, it has become a hot point in the optical communication field of a dense wavelength division multiplexing (DWDM) system. In addition, with the increase of the transmission capacity and channel numbers for optical communication systems and the growth of the transmission speed in each channel, the researches of ultra-long haul optical communication systems have become a hot subject.

As one of the vital devices in high-speed ultra-long haul optical communication systems, the RA has the function to improve the Signal Noise Ratio (SNR) and to extend the transmission distance. Because the characteristics of the RA are related to its Amplified Spontaneous Emission (ASE) noise, Raman crosstalk, double Rayleigh backscattering (DRB) noise and so forth^[1-5], it is necessary to understand fully the impacts of the noises of the RA on its performance for the optimum design of the RA. This is the aim of the work in the paper.

2 Analysis on ASE noise of RA

The documents[1], [2] and [3] have proposed the full form of the Raman coupling equations including the ASE noise, Rayleigh noise and temperature effects, however, these equations are not convenient in the numerical simulation. So the equations in the document^[4] are applied in this paper:

$$\frac{dP_{pi}}{dz} = \alpha_p P_{pi} + \sum_j \left(\frac{g_{ji}}{K} P_{pi} P_{sj} + g_{ji} P_{pi} h v_{sj} \Delta v \right), \quad (1)$$

$$\frac{dP_{sj}}{dz} = -\alpha_s P_{sj} + \sum_i \left(\frac{g_{ji}}{K} P_{pi} P_{sj} + g_{ji} P_{pi} h v_{sj} \Delta v \right), \quad (2)$$

Where, P_{pi} , P_{sj} is separately the pump power and signal power, α_p , α_s is the attenuation coefficient for pump and signal respectively, $K=1$ under the same condition of the polarization direction for the signal and pump, or $K = \infty$ under the orthogonal condition, or $K = 2$ under the complete disordered condition, g_{ji} is the Raman Gain coefficient, h is Planck's constant, v_{sj} is optical frequency, Δv is optical bandwidth. According to the formula (1) and (2), incoherent spontaneous emission can occur at any point in the RA, parts of the emission can be coupled into light waveguides, and they not only attenuated but also amplified by the pump light in the transmission process. Therefore, it is necessary to acquire the transmission characteristics of the pump light to calculate the ASE noise of the RA and further get the Raman gain at any point in an optical fiber. The document^[4] introduced how to obtain the ASE noise. According to the document^[4], the relationship among the number of the ASE noise photons, the fiber loss and Raman switching gain can be expressed as follow:

$$N_{Rj}(L) = K \left\{ \frac{G_{Rj}}{\exp(\alpha L)} - 1 + \frac{G_{Rj} - 1}{\ln G_{Rj}} \right\}, \quad (3)$$

where L is the fiber length, G_{Rj} is the switching gain of the signal, and N_{Rj} is the number of the ASE noise photons at the end of the fiber. The formula (3) is the basis of the analysis of performance influences of the RA on the ASE noise discussed later.

According to the formula (3), the RA is compared with the EDFA in this paper. Firstly we compare the number of the ASE noise photons generated by the RA and by the EDFA under the same gain, respectively, and the hypothesis condition is that the amplifier gain compensates for the fiber losses completely. The number of the ASE noise photons produced by the

EDFA is defined as^[6]:

$$N_E = 2n_{sp}(G_E - 1), \quad (4)$$

Under the condition of the same signal input, the improvement of the OSNR of the RA compared with that of the EDFA is:

$$\Delta OSNR = 10 \lg \left(\frac{OSNR_{RA}}{OSNR_E} \right) = 10 \lg \left(\frac{N_E}{N_R} \right), \quad (5)$$

In Fig. 1 and Fig. 2, the limit value of the spontaneous emission factor n_{sp} is 1, and $k = 2$. It is obvious from Fig. 1 and 2 that, under the condition of the same signal input, when amplifiers compensate the fiber losses fully, the greater the losses, i. e., the greater the gain, the greater the ratio of the number of ASE photons produced by the EDFA to that caused by the RA, and the higher the improvement of the OSNR of the RA, compared with that of the EDFA. It is also can be seen that $\Delta OSNR$ linearly increases with the gain early and then reaches the saturation state.

Imitating the formula (4), the equivalent

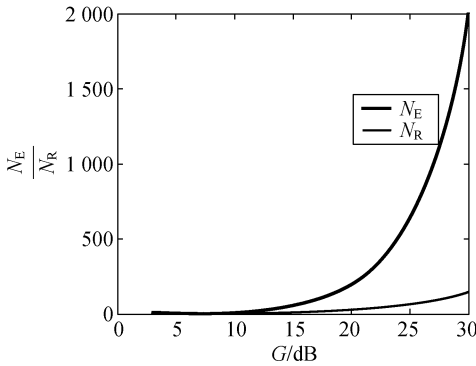


Fig. 1 N_E and N_R at different gains

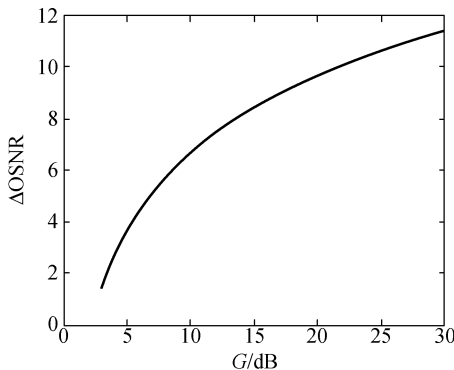


Fig. 2 $\Delta OSNR$ at different gains

spontaneous emission factor of the RA is defined as:

$$n_{sp}^R = \frac{N_R}{2(G_R - 1)}, \quad (6)$$

The relationship between the equivalent n_{sp}^R of the RA and the switching gain is described in Fig. 3, from which it can be seen that the value of n_{sp}^R is evidently less than 1, and decreases with the increment of the switching gain. This characteristic of the RA is extremely superior to that of the EDFA with the reason that the limit value of its n_{sp} is 1.

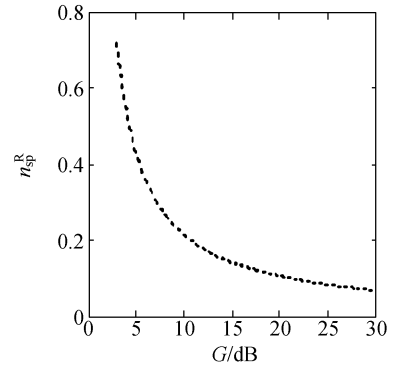


Fig. 3 Change of n_{sp}^R for RA with switching gains

According to the documents [1] and [4], the Equivalent Noise Factor (ENF) of the RA can be defined as:

$$ENF = \frac{1 + N_R}{G_R}, \quad (7)$$

The relationship between the ENF of the RA and the switching gain is shown in Fig. 4, where the ENF is negative when the gain is above 5 dB. However, the limit value of the noise factor (NF) for the EDFA is 3. All above indicate that the RA has the intrinsic characteristics of low noise.

The ASE lights described by the formula (3) produce the beat frequency with signals in square optical receivers, and generate the ASE noise current. For ‘0’ code and ‘1’ code, the power of this beat frequency noise current is expressed as^[7]:

$$\sigma_{ASE}^2(0) \approx 0, \sigma_{ASE}^2(1) = 4B_e \times (2P_m \mathcal{R}) \times [P_{ASE}^{RA}(v_s, L) \mathcal{R}], \quad (8)$$

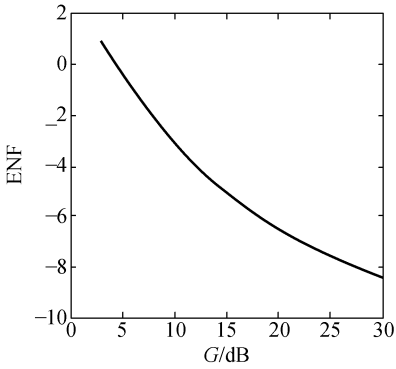


Fig. 4 ENF of RA

Where \mathcal{R} , B_e and P_{in} are respectively the sensitivity, the bandwidth of electrical filter and the average signal optical power of optical receiver. The SNR of the optical receiver under the condition that the ASE noise is considered only is:

$$SNR_{ASE} = 10 \lg \left[\frac{2(\mathcal{R}P_{in})^2}{\sigma_{ASE}^2(0) + \sigma_{ASE}^2(1)} \right] = 10 \lg \left[\frac{P_{in}}{4B_e N_R h \nu_s} \right], \quad (9)$$

The change of the SNR with the switching gains is shown in Fig. 5. The parameters in Fig. 5 are: $\alpha_s = 0.22$ dB/km, $L = 100$ km, $B_e = 7.5$ GHz, $\nu_s = 191$ T, and the input signal power in Fig. 5 is 1 mW. From Fig. 5, it is obvious that after the Raman switching gain is above 10 dB, the ASE noise performance will gradually become good with the increase of the switching gain.

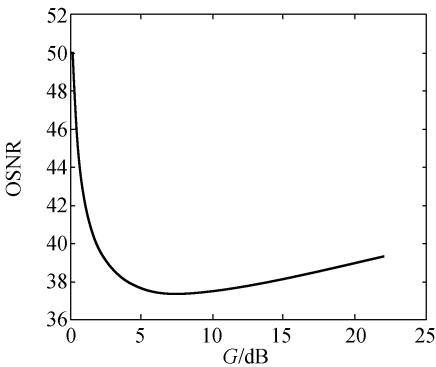


Fig. 5 Change of SNR with switching gains

3 Analysis on DRB noise of RA

The noise characteristics of the RA is related to the amplified ASE noise, Raman crosstalk, DRB and so on, while the DRB is one of the major influencing factors in long-haul optical communication systems. Because the DRB noise is accumulated and amplified in optical communication systems with tens of kilometers fibers, and greatly influences the system performance^[3-5].

Because the light frequency of the DRB noise is the same as that of the signal, the beat frequency noise current can be produced through the interaction between the front optical filter of the receiver and the signal light, and the noise of Intensity Modulation Direct Detection (IM-DD) system can't be removed off by the electrical filter, the methods to control the DRB noise are very limited so far^[7]. For this reason, the theoretical calculation for the DRB is done in this paper, First of all, the switching gain between any two points in fibers can be deduced as follows according to the coupling equations:

$$G(z_1, z_2) = \exp[\ln G_{RA} \times (e^{\alpha z_2} - e^{\alpha z_1}) / (e^{\alpha L} - 1)], \quad (10)$$

Where, G_{RA} is the switching gain of the RA at the point $z=L$. The transmission characteristics of the signal lights in fibers can be obtained by using the formula (10):

$$P_S(z) = P_{in} \exp\{-\alpha z + \ln G_{RA} \cdot [\exp(\alpha z) - 1] / [\exp(\alpha L) - 1]\}, \quad (11)$$

Then, the electric field intensity of the DRB is calculated.

Assume that the signal light source is a linearly-polarized light, its electric field intensity may show as follows^[3]:

$$e(t) = \text{Re}[\epsilon_S(t) e^{j2\pi f_0 t}]. \quad (12)$$

Where, $\text{Re}[\cdot]$ represents the real part, f_0 is the carrier frequency, $\epsilon_S(t)$ shows the complex number amplitude of the electric field, including the magnitude of the amplitude and the beginning phase, $P_{in} = |\epsilon_S(t)|^2$.

When polarization changes of the linearly-polarized light of the signal sources in the transmission process is not in consideration, the electric field intensity in the direct transmission process can be described as follow according to the document^[8]:

$$\epsilon_{\text{dir}}(t, z) = \epsilon_s(t - \frac{z}{v}) e^{-(\alpha/2 + j\beta)z} \sqrt{G(0, z)}, \quad (13)$$

Where, v and β are respectively the group velocity and phase velocity in fibers.

Fig. 6 shows the principle of the double Rayleigh backscattering process.

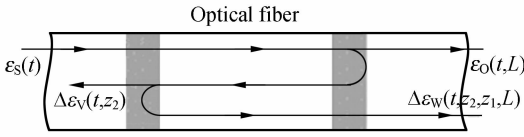


Fig. 6 Scheme of double Rayleigh backscattering process

In the course of the transmission, a part forward light near the z_2 is reflected into the reverse wave-guide, and becomes into the first Rayleigh backscattering light, its electrical field intensity may be shown as follows:

$$\Delta\epsilon_{\text{RB}}(t, z_2) = \epsilon_s(t - \frac{z_2}{v}) e^{-(\alpha/2 + j\beta)z_2} \sqrt{G(0, z_2)} \rho(z_2) \Delta z_2, \quad (14)$$

Where, $\rho(z)$ is the coefficient of the differential Rayleigh backscattering and a complex number.

Through the Rayleigh backscattering again, $\Delta\epsilon_{\text{RB}}$ can be turn into the electrical field intensity in the fiber end of the double Rayleigh backscattering and be described as follow:

$$\Delta\epsilon_{\text{DRB}}(t, z_2, z_1, L) = \epsilon_{\text{dir}}(t - 2 \frac{z_2 - z_1}{v}, L) e^{-(\alpha + j2\beta)(z_2 - z_1)} G(z_1, z_2) \rho(z_1) \rho(z_2) \Delta z_1 \Delta z_2, \quad (15)$$

Thus, through the integration for the formula (15), the total electrical field intensity of the DRB can be described as follows:

$$\epsilon_{\text{DRB}}(t, L) = \int_0^L \int_0^{z_2} \epsilon_{\text{dir}}(t - 2 \frac{z_2 - z_1}{v}, L) \cdot e^{-(\alpha + j2\beta)(z_2 - z_1)} G(z_1, z_2) \rho(z_1) \rho(z_2) dz_1 dz_2, \quad (16)$$

The optical power at the end of the fiber can be acquired by the combination of the formula (13) and (16):

$$I(t) = |\epsilon_{\text{dir}}(t, L)|^2 + |\epsilon_{\text{DRB}}(t, L)|^2 + 2\text{Re}[\epsilon_{\text{dir}}(t, L) \epsilon_{\text{DRB}}^*(t, L)], \quad (17)$$

Where, the most component of the Rayleigh noise is composed of the beat frequency caused by the DRB and the direct transmission signals.

And then the polarization-changing effect caused by the optical fiber transmission is taken into account. Because the beat frequency occurs only when two light beams have the same polarized direction, the third item in the formula (17) should be $\sqrt{5/9}$ times according to document^[9], that is:

$$I_{\text{DRB}}(t) = \sqrt{5/9} \times 2\text{Re}[\epsilon_{\text{dir}}(t, L) \epsilon_{\text{DRB}}^*(t, L)], \quad (18)$$

For a digital Intensity Modulation-Direct Detect (IM-DD) system, the noise current produced by the beat frequency can fully pass through the electrical filter of optical receivers^[3, 10], whose noise currents can be attained by the optical power represented by the formula (18) multiplied by the sensitivities of optical receivers. Thus, when transmitting '0' code and '1' code, the average power of the DRB noise current can be shown as follows:

$$\sigma_{\text{DRB}}^2(0) \approx 0, \sigma_{\text{DRB}}^2(1) = 2 \times \mathcal{R}^2 \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \langle I_{\text{DRB}}(t) \cdot I_{\text{DRB}}(t) \rangle dt, \quad (19)$$

Where, $\langle \cdot \rangle$ represents the ensemble average. According to the document [8] and [10], the formula (19) can be deduced as follows:

$$\sigma_{\text{DRB}}^2(1) = \frac{20}{9} \mathcal{R}^2 (\alpha_r S)^2 [R_{\epsilon}^{\text{dir}}(0)]^2 \int_0^L \int_0^{z_2} e^{-2\alpha(z_2 - z_1)} \cdot G^2(z_1, z_2) dz_1 dz_2, \quad (20)$$

Where, $R_{\epsilon}^{\text{dir}}(\tau) = \overline{\epsilon_{\text{dir}}^*(\cdot + \tau, L) \cdot \epsilon_{\text{dir}}(\cdot, L)}$, the overbar represents the time average, $R_{\epsilon}^{\text{dir}}(0)$ and \mathcal{R} are the average optical power and sensitivity of optical receivers, respectively, and the α_r , S represent the Rayleigh scattering factor and recapture factor, respectively. The following equation can be deduced by taking the formula (10) into the formula (20).

$$\sigma_{\text{DRB}}^2(1) = \frac{20}{9} [\mathcal{R}\alpha_r, \text{SR}_\epsilon^{\text{dir}}(0)]^2 \times \left\{ \frac{e^{-\alpha L} - 1}{\alpha^2 b} + \frac{e^{-2\alpha L} - 1}{2\alpha^2 b^2} + \frac{e^{-b}(1+b)}{\alpha^2} \int_b^{be^{\alpha L}} \frac{e^x}{x^3} dx \right\}, \quad (21)$$

Where, $b = 2 \ln G_{\text{RA}} / (e^{\alpha L} - 1)$, According to the formula [2] and [24], The SNR of the receiver under the condition of only taking the Rayleigh noise into account is expressed as follows.

$$\text{SNR}_{\text{DRB}} = 10 \times \ln \{ 2\mathcal{R}\mathcal{R}_\epsilon^{\text{dir}}(0)^2 / [\sigma_{\text{DRB}}^2(0) + \sigma_{\text{DRB}}^2(1)] \}, \quad (22)$$

The curve drawing for the change of the SNR of optical receivers with the Raman gain is shown in Fig. 7, where, $\alpha_r = -42$ dB, $S = -27$ dB, $L = 80, 120, 160$ km, and the input optical power is random. From the Fig. 7, it can be seen that whether the Raman gain increase or the length of fibers extends, the DRB noise performance of the RA always deteriorates. This is different from the thing of Fig. 5.

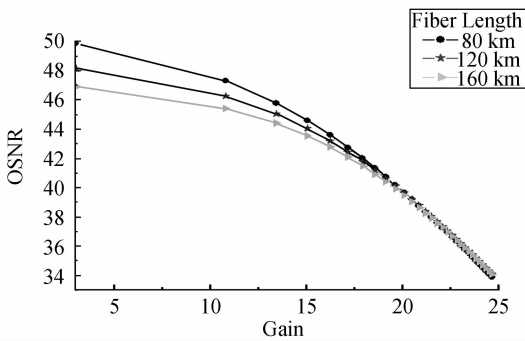


Fig. 7 SNR of receiver under condition of only taking Rayleigh noise into account

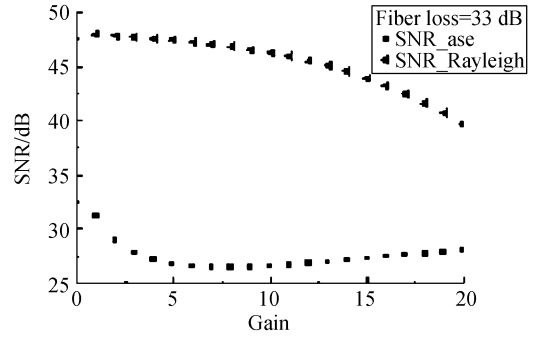
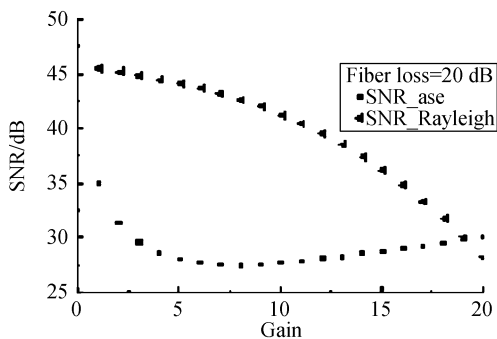


Fig. 8 Relationship between SNRs of optical receivers and switching gains of RA

Fig. 8 describes the relationships between the SNRs of optical receivers and the switching gains of the RA when the fiber losses are 20 dB and 33 dB in consideration of the ASE noise only and Rayleigh noise only, respectively. From Fig. 8, it can be seen that if the fiber length is constant, the ASE noise is the most component of the amplifier noise when the switching gain is small; so the Rayleigh noise can be ignored; however, when the switching gain becomes greater, the Rayleigh noise sharply increases and is possible to surpass the ASE noise. When the gain of the RA is less than 15 dB, the Rayleigh noise can be neglected.

4 Conclusions

This paper analyses and discusses theoretically ASE noise, equivalent spontaneous emission factor, the ENF of RA and the SNRs of optical receivers when the ASE noise is only taken into account, and also probes theoretically the Rayleigh noise of the RA and the SNRs of optical receivers when Rayleigh noise is only taken into account. Then, it analyzes the impacts of the switching gain and fiber length in the RA on the SNRs of optical receivers, and implements the numerically related simulations. The calculation and simulation results show that the RA can improve the SNRs of optical receivers under the condition of the same input signal compared with

the EDFA and the equivalent spontaneous emission factor is less than 1 and decreases with the increase of the switching gain, so this characteristics of the RA are superior to that of the EDFA. Moreover, the condition that the Rayleigh

noise of the RA can be ignored is that the gain of the RA is less than 15 dB. In addition, some other significant conclusions to play an important role in guiding the optimal design of the RA are also obtained.

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